

Thermal Design and On-Orbit Performance of the Multi-angle Imaging SpectroRadiometer

José I. Rodriguez and David J. Diner

Jet Propulsion Laboratory, California Institute of Technology

Copyright © 2001 Society of Automotive Engineers, Inc.

ABSTRACT

The Multi-angle Imaging SpectroRadiometer (MISR) instrument was launched aboard NASA's Earth Observing System (EOS) Terra spacecraft on December 18, 1999. The overall mission design lifetime for the instrument is 6 years. The EOS Terra spacecraft was placed in a sun-synchronous near-circular polar orbit with an inclination of 98.3 degrees and a mean altitude of 705 km. The overall objective of MISR is to provide a means to study the ecology and climate of Earth through the acquisition of global multiangle imagery on the daylight side of Earth. MISR views the sunlit Earth simultaneously at nine widely spaced angles, collects global images with high spatial detail in four colors at every angle. The images acquired, once calibrated, provide accurate measurements of brightness, contrast and color of reflected sunlight. Changes in the reflection at different view angles provides a means to distinguish between different types of atmospheric particles (aerosols), cloud forms and land surface covers. Using stereoscopic techniques, MISR data enables construction of 3-dimensional models and more accurate estimates of the total amount of sunlight reflected by Earth's diverse environments.

The thermal design provides three temperature zones required by the instrument, namely -5°C , 5°C and 20°C . The charged-couple device (CCD) detectors are cooled by solid state single-stage thermoelectric coolers (TECs) which dump their waste heat to nadir radiators. Nadir radiators provide cooling for the optical bench and all nine cameras with camera head electronics. The remaining electronics are cooled to ambient temperatures near 20°C with separate nadir radiators.

The thermal control system (TCS) consists of passive and active elements to maintain the instrument within allowable flight temperature limits (AFTs). Passive thermal control includes multi-layer insulation (MLI) blankets, thermal straps, and surface coatings to manage the transfer of waste energy from sources through structures and ultimately to nadir radiators.

Active thermal control employs TECs and close-loop heater control systems for the detectors and optical bench. Operational and replacement heaters are used in the instrument science and safe modes and survival heaters are used in the survival mode. This paper describes the instrument thermal requirements, thermal design, key drivers for the design process and analysis results. The on-orbit performance to date is also presented.

INTRODUCTION

The MISR instrument, designed and built by the Jet Propulsion Laboratory (JPL) for NASA, is currently flying onboard the EOS Terra spacecraft. The Terra spacecraft was launched successfully on December 18, 1999 at 10:57:39 AM pacific standard time (PST) aboard an Atlas IIAS vehicle from Vandenberg Air Force Base in California. After initial spacecraft checkout and deployment of the solar panels, the survival heaters were turned on about noon PST. Instrument powered on occurred on December 21, 1999 at 12 noon PST. Subsequent to this event MISR was placed in safe mode for an extended outgassing period. After opening the optical bench cover, MISR acquired its first image of Earth's surface on February 24, 2000 at 16:40 coordinated universal time (UTC).

The EOS Terra project is managed by NASA's Goddard Space Flight Center. As the first mission of NASA's EOS Program, the Terra satellite hosts a suite of five scientific instruments three of which are designed to measure quantities related to Earth's energy budget including aspects of both reflected sunlight and thermal energy emitted by Earth. The satellite's orbit was selected to allow measurements to be taken at all latitudes with complete coverage of the entire globe in 16 days. The EOS Terra instruments ASTER, CERES, MISR, MODIS, and MOPITT have unique and complementary capabilities which will enable new research into the ways that Earth's lands, oceans, air, ice and life function as a global environmental system. MISR's role is to measure the amount of sunlight that is scattered in different

directions under natural conditions. This will provide information on the amount of solar energy that heats Earth's surface and atmosphere, and the changes that occur in these quantities over the six-year nominal lifetime. A detailed description of MISR and its science capabilities is found in Refs. 1-3. The goal of NASA's EOS program is to increase our understanding of the climate changes that are occurring on planet Earth, and the reasons for these changes in order to be better equipped and anticipate for the future. An artist's conception of the EOS Terra spacecraft on orbit is shown in Fig. 1. The spacecraft without external MLI blankets is shown in Fig. 2.

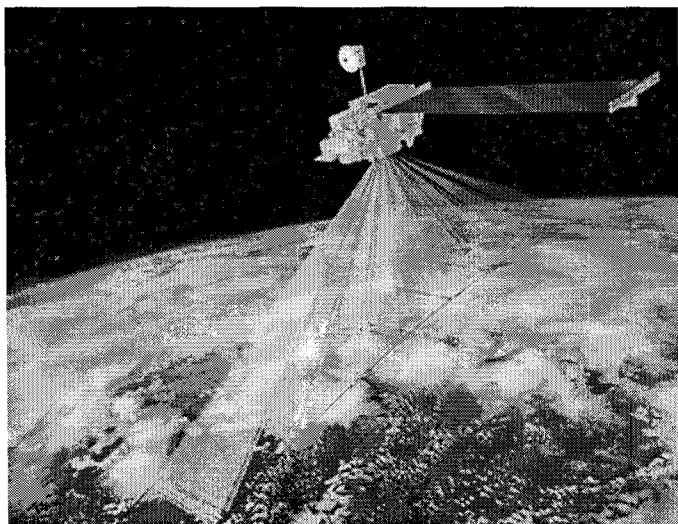


Figure 1. EOS Terra spacecraft in orbit showing MISR camera views looking at Earth

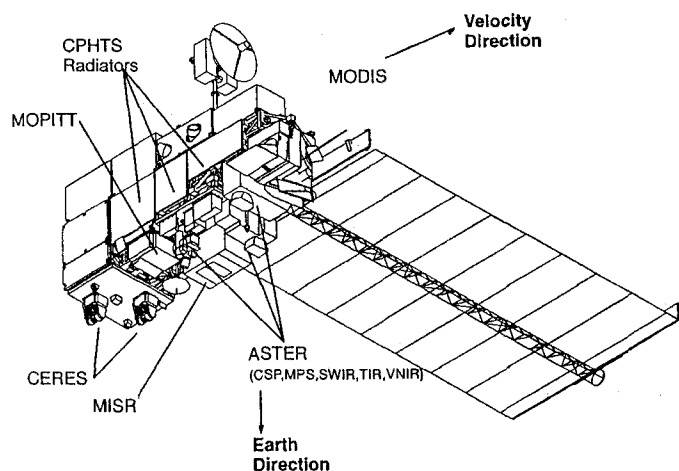


Figure 2. EOS Terra spacecraft configuration

INSTRUMENT DESCRIPTION

MISR is a new type of instrument that views Earth with cameras pointed in nine different directions. As the instrument flies overhead, each section of the planet's

surface below is successively imaged by all nine cameras in each of the four color bands (blue, green, red, and near-infrared). Consequently, MISR is referred to as a pushbroom camera instrument. The viewing geometry for MISR's cameras looking at Earth is shown in Fig. 3. The scattering angle is the angle between the direction of the incoming light and the viewing direction. Observations at different scattering angles provides the information needed to study clouds, haze and dust particles in the air. The viewing swath is 360 kilometers. Each of the nine cameras observes at different scattering angles and these angles change with latitude position. It is the wide range of scattering angles coupled with the moderately high spatial resolution imaging that makes MISR unique.

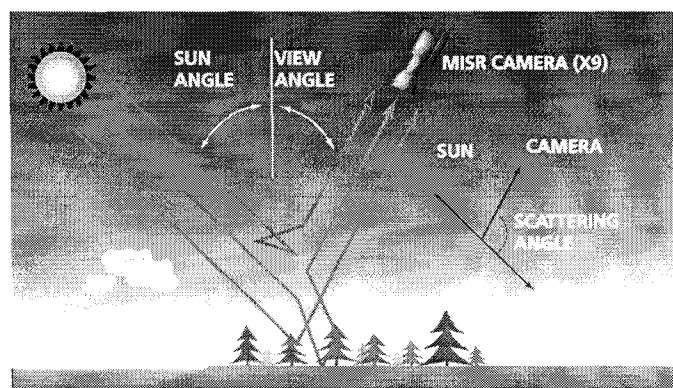


Figure 3. Viewing geometry for a satellite camera looking at Earth

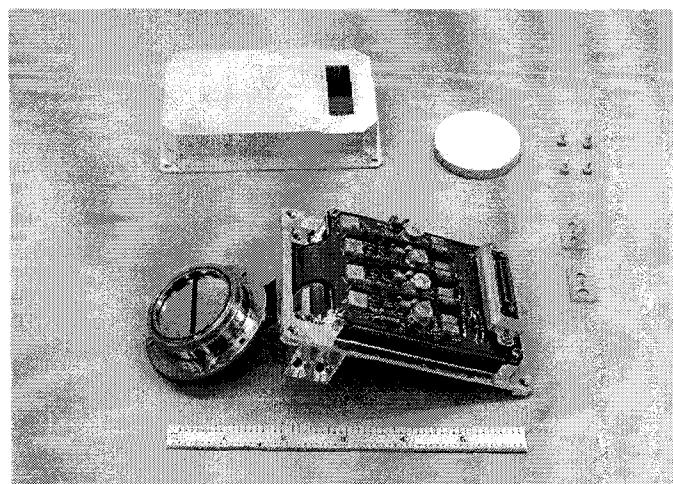


Figure 4. Camera head electronics with CCD focal plane

The heart of the MISR instrument is the CCD focal plane arrays, located in each of the nine cameras, cooled to -5°C by a solid state TEC (Fig. 4). The camera optics, camera head electronics and optical bench are maintained at 5°C by means of the optical bench nadir radiator. All nine cameras use a CCD architecture with 4 lines by 1504 active pixels. The instrument four

spectral bands are 446.4, 557.5, 671.7 and 866.4 nanometers and the corresponding spectral bandwidths are 41.9, 28.6, 21.9 and 37.9 nanometers. The camera view zenith angles at Earth's surface are 0.0 (nadir), 26.1, 45.6, 60.0, and 70.5 (both fore and aft of nadir) degrees. The cross-track and along-track coverage is 275 meters by 275 meters and it has a commandable pixel sampling coverage of 550 meters by 550 meters, 1.1 km by 1.1 km and 275 meters by 1.1 km.

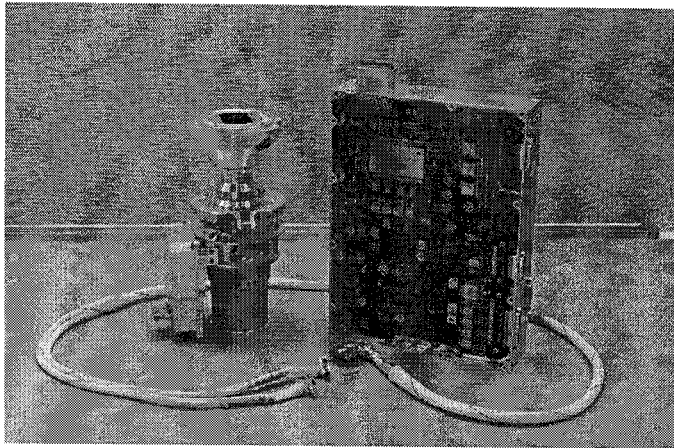


Figure 5. Camera optics with camera head electronics and camera support electronics

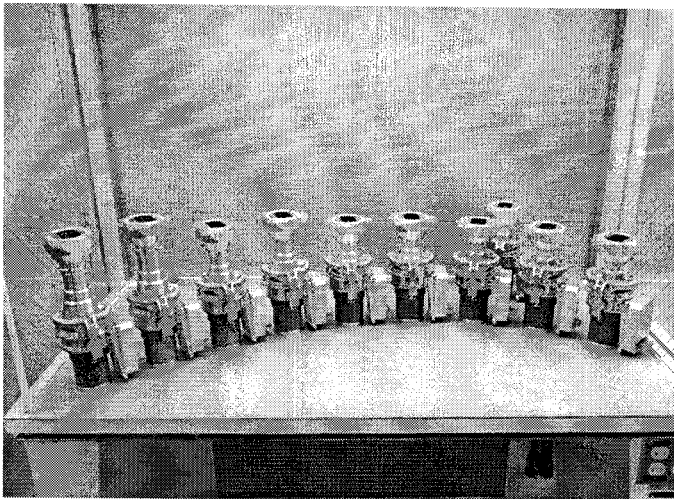


Figure 6. MISR's nine cameras with camera head electronics and the spare nadir camera

A complete camera assembly with its associated camera support electronics is shown in Fig. 5. The instrument includes nine complete sets of camera assemblies and two sets of system electronics for redundancy. Fig. 6 shows all nine cameras including the spare nadir camera.

All nine cameras are attached to the optical bench. Fig. 7 shows the instrument layout. The optical bench provides the structural support as well as the thermal

control interface for all nine cameras. The all-aluminum optical bench assembly maintains the critical alignment required by the cameras at the operating temperature (Fig. 8). The optical bench with its nine cameras are showing in Fig. 9.

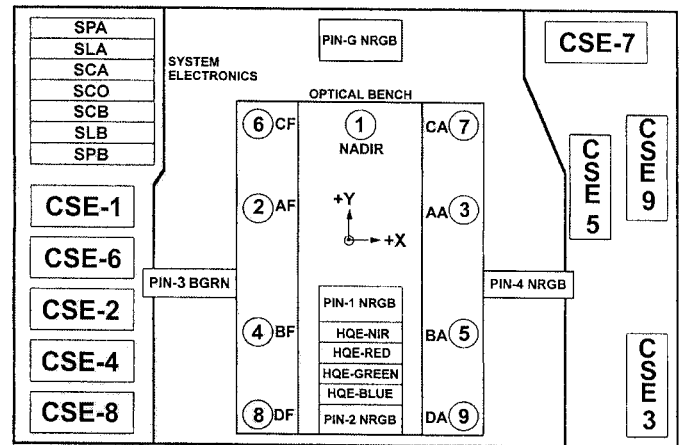


Figure 7. Instrument layout configuration

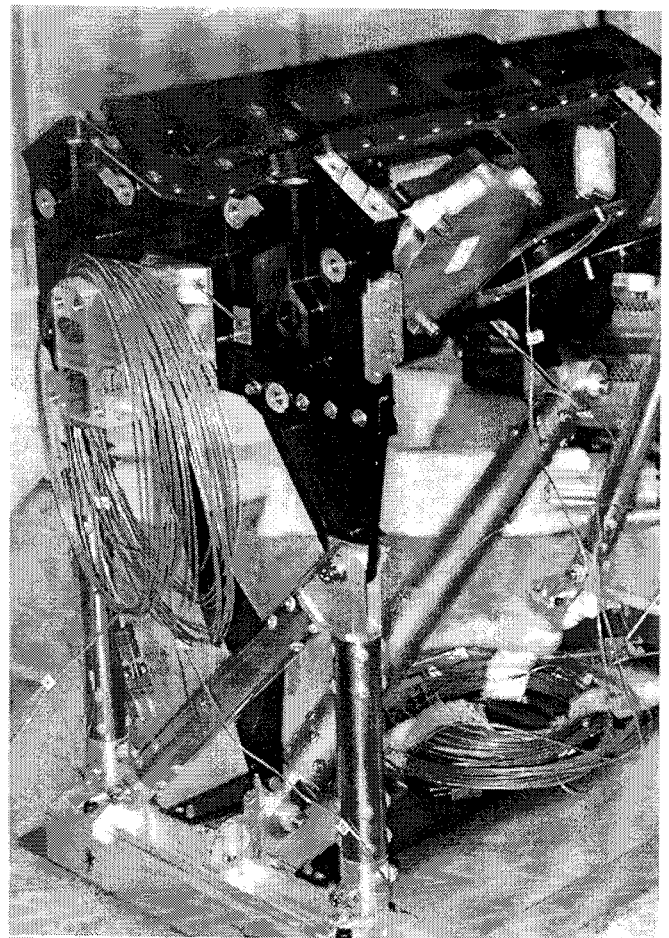


Figure 8. All-aluminum optical bench with titanium struts

MISR is housed within a composite primary support structure (PSS) designed and fabricated by Space

Systems Loral under contract to JPL. The instrument envelope is 1.27 meters by 0.9 meters by 0.99 meters and weighs approximately 149 kg. The average and peak operating powers are 104 W and 127 W, respectively. The instrument PSS is built with honeycomb sandwich panels fastened either with permanently bonded clips or removable longerons and fasteners (Fig. 10). The sandwich panels are constructed from composite facesheets made of Fiberite M60J/954-2A unidirectional graphite-cyanate and 2 lb/ft³ 5056 aluminum honeycomb core. The facesheets are constructed using 2 mil plies in a pseudo-isotropic configuration. Fig. 11 shows the PSS composite panels. The optical bench is mounted on threaded inserts in the PSS and the support electronics are mounted onto the support shelves with structural inserts (Fig. 12). The instrument is attached to the spacecraft using four kinematic mounts, which contain spherical bearings. These mounts provide quasi-statically determinate boundary conditions for the instrument. Ref. 4 describes the detailed design, fabrication, proof and dynamic test of the PSS.

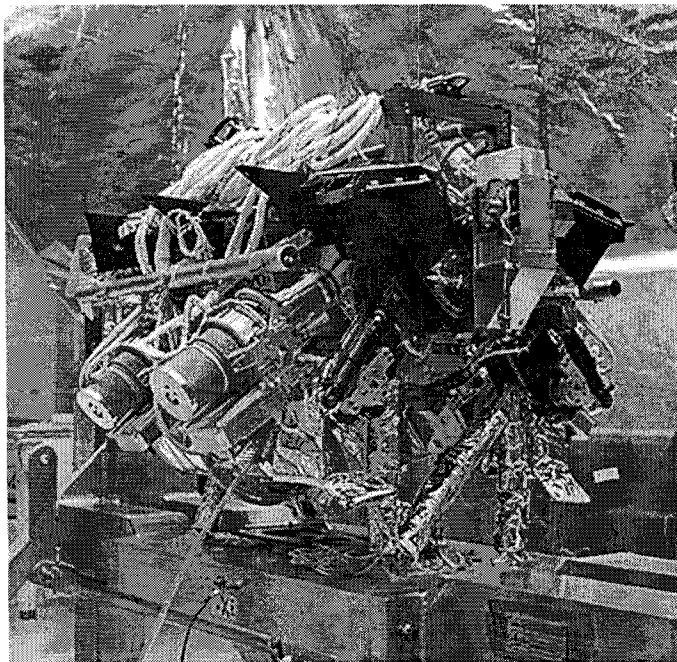


Figure 9. Optical bench assembly with all nine cameras

The instrument design includes glint baffles in the -X, +X and +Y sides at the top of instrument (+Z face) above the nadir radiators. These baffles are needed to block direct solar and scattered sunlight from other instruments and spacecraft surfaces. The -X baffle was fabricated with a 10 mil Kapton sheet bonded to a G10 rod frame. The remaining baffles were constructed from thin aluminum

sheet metal. Figs. 13-16 show the flight instrument with external MLI blankets.

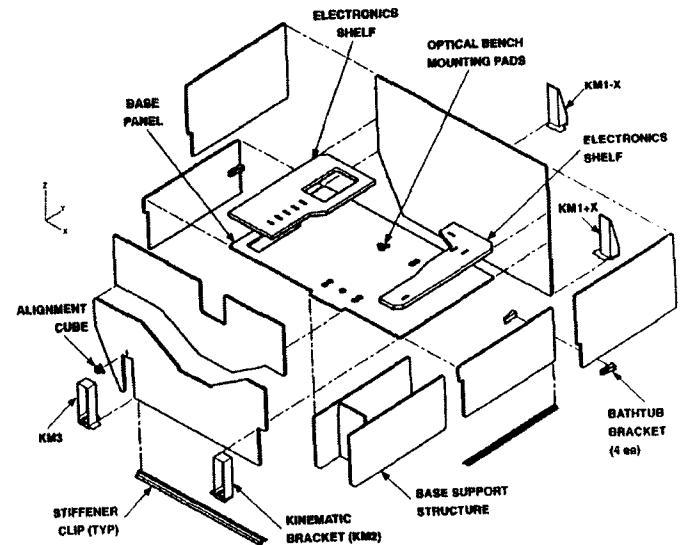


Figure 10. Schematic of primary support structure

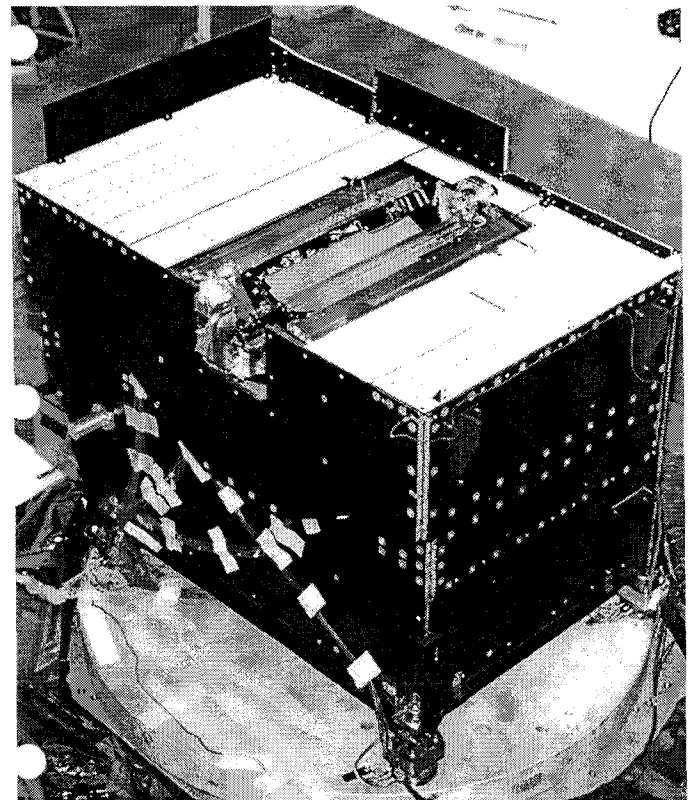


Figure 11. Instrument primary support structure

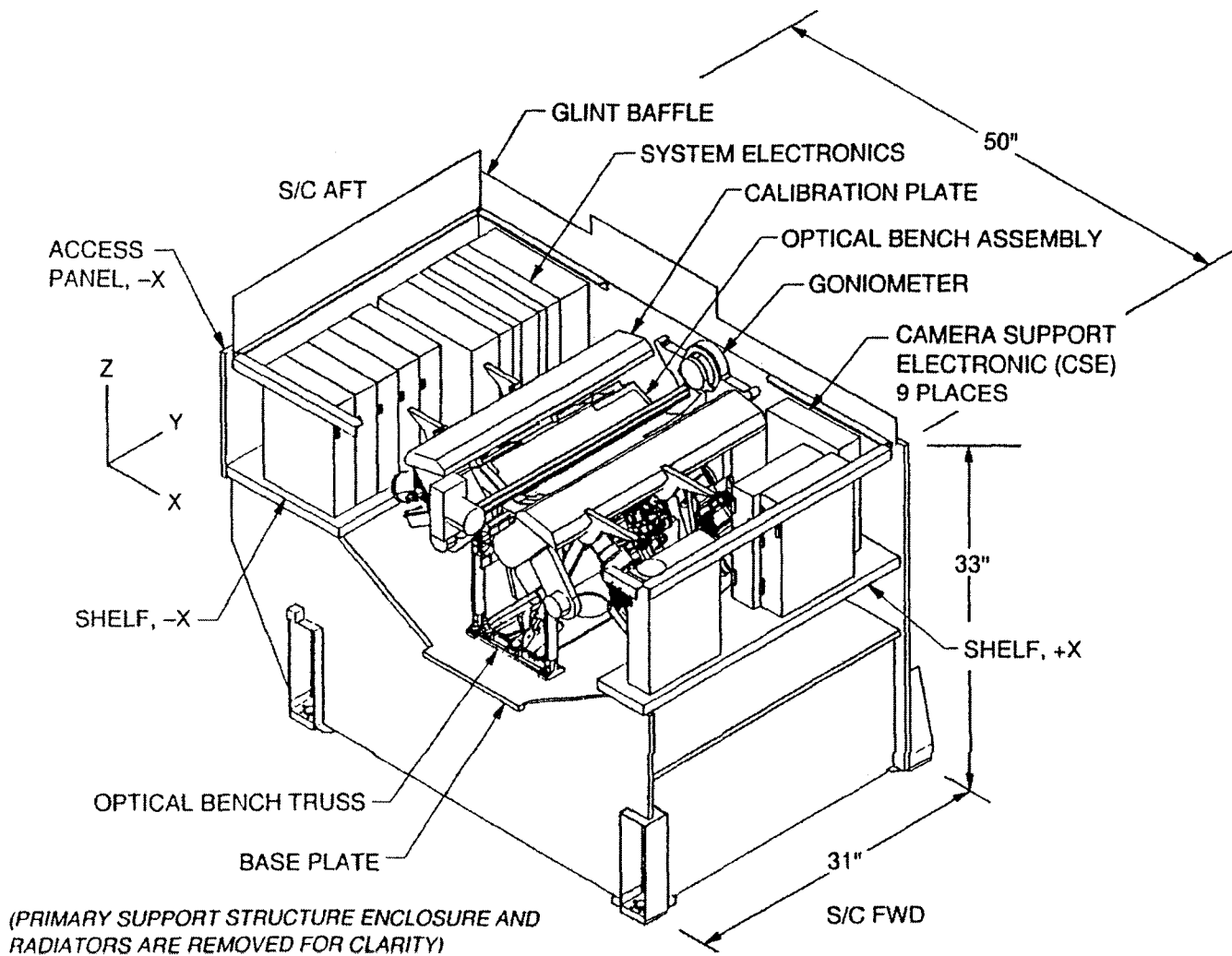


Figure 12. Instrument configuration.

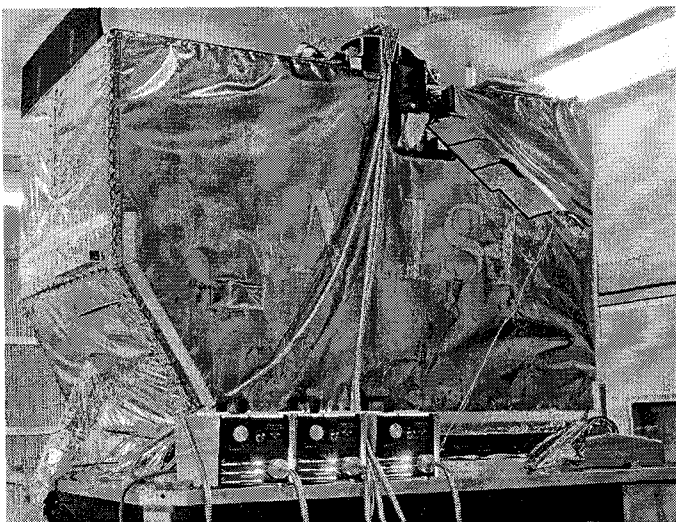


Figure 13. MISR instrument with optical bench cover deployed: -X,-Y isometric view

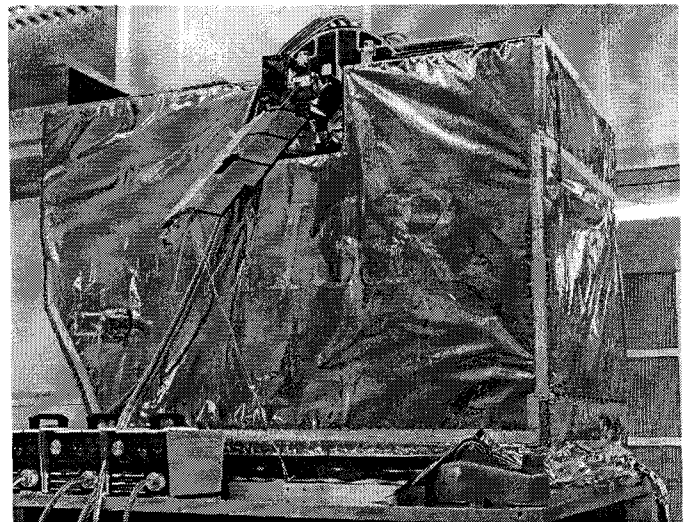


Figure 14. MISR instrument with optical bench cover deployed: +X,-Y isometric view

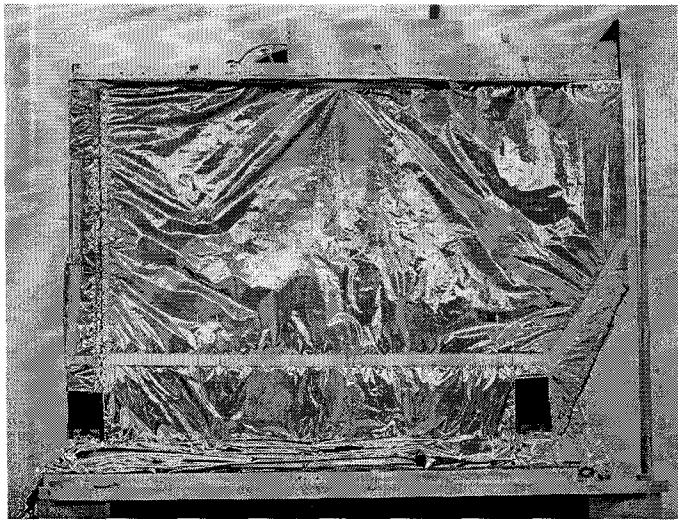


Figure 15. MISR instrument: +Y view

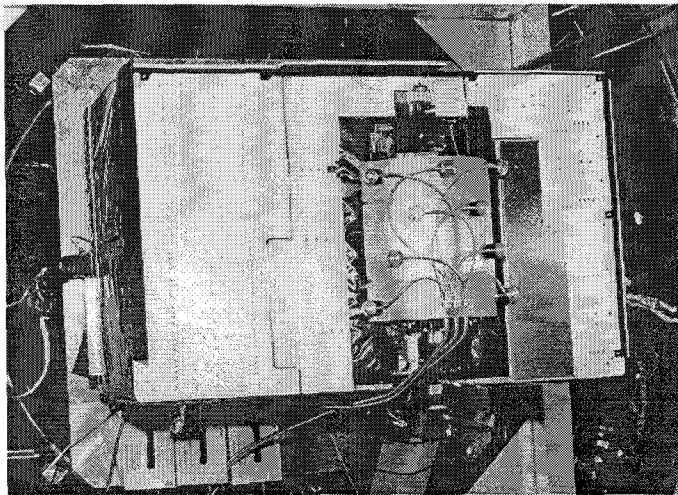


Figure 16. MISR instrument: +Z view (top)

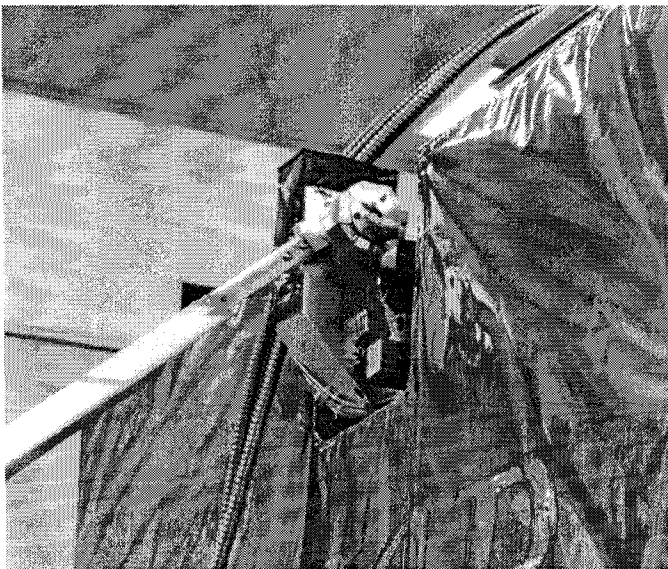


Figure 17. Optical bench cover mechanism: partly deployed position

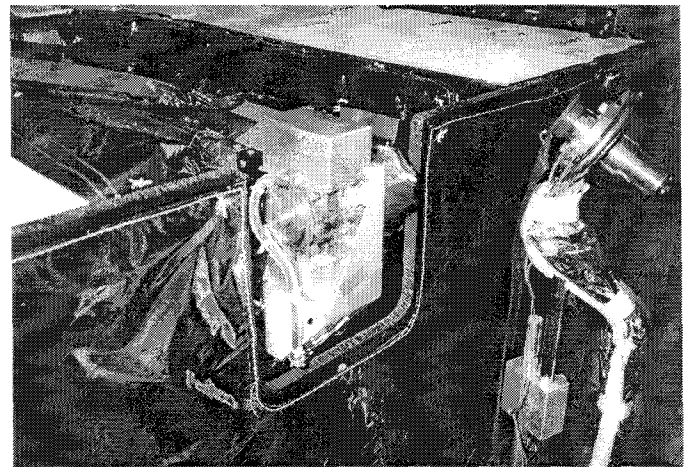


Figure 18. Optical bench cover mechanism: stowed position

SPACECRAFT ENVIRONMENTS

The key drivers for the MISR thermal design are as follows:

- Orbit parameters: sun-synchronous, near-circular orbit, 705 km altitude, 10:30 am \pm 15 min descending node, 98.3 degree orbit inclination
- Spacecraft interface temperatures: 0/+30°C for normal operation and -25/+50°C during survival mode
- Heat transfer to spacecraft is limited to 15.5 W/m², which includes radiation and conduction heat transfer

The parameters and conditions of each spacecraft state defining the hot and cold mission environments, safe and survival spacecraft attitudes and the solar vector to orbit plane (beta) angle is shown in Table 1. The environmental constants used are defined in Table 2. Figs. 19 and 20 define the science, survival and safe orbits.

Table 1. EOS Terra spacecraft mission environments

S/C state	Beta angle (degrees)		S/C Attitude	Description
	hot	cold		
Launch	varies	varies	varies	Includes ascent, coast, orbit insertion to power on. Aperture cover stowed
Science	13.5	30	+Z local vertical (nadir pointing)	Aperture cover deployed
Safe	30.8	15	-X solar inertial (sun pointing)	Aperture cover deployed
Survival	NA	15	+Z local vertical (nadir pointing)	Aperture cover deployed

Table 2. Mission environment parameters

Parameter	Cold Case	Hot Case
Solar Flux	1350 W/m ²	1412 W/m ²
Albedo	0.315	0.336
Earth IR	229 W/m ²	243 W/m ²

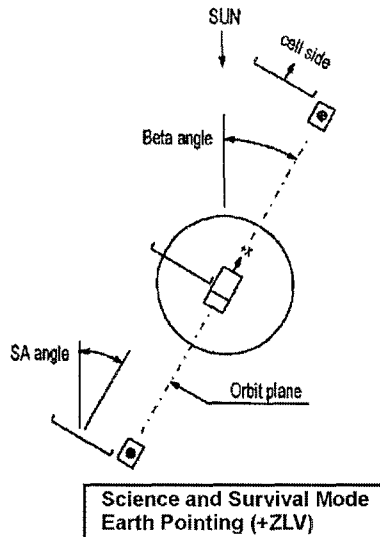


Figure 19. Terra spacecraft science and survival orbit definitions

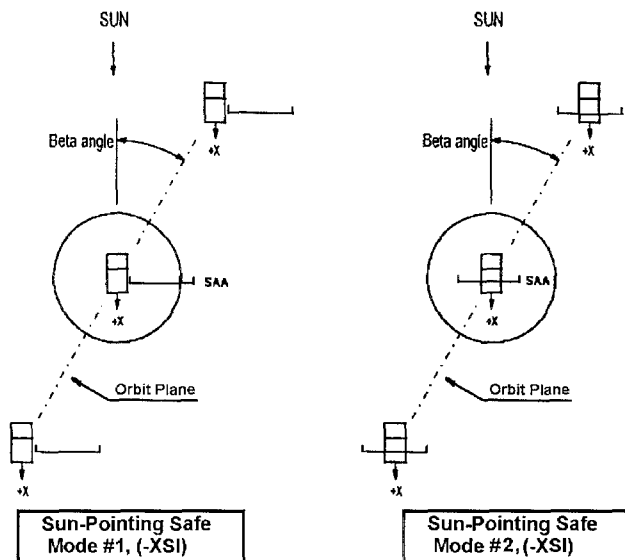


Figure 20. Terra spacecraft safe mode orbit definitions

THERMAL DESIGN REQUIREMENTS

The instrument thermal requirements along with spacecraft mission environments pose a challenging thermal design problem. Spacecraft requirements dictate that the instrument thermal control be

independent of the platform. This leads to the use of MLI blankets and titanium thermal isolator mounts to provide the required thermal isolation. In addition, passive nadir pointing heat rejection radiators are required to reject the instrument power dissipation. To provide cooling to the focal plane assemblies, a TEC was required.

The key temperature control requirements are listed in Table 3. The instrument power dissipation is shown in Table 4. The camera electronics are turned off on the night portion of the orbit as a means to conserve power and keeping within the data rate limits. The instrument exterior is covered with MLI blankets with the exception of the nadir viewing radiators.

Table 3. Allowable flight temperature requirements

	Allowable Flight Temperatures (°C)			
	Non-operating	Operating		
	Survival	Orbit Var.	Grad	Design
Camera Support Electronics	-25/50	10 ⁽¹⁾		-10/40
System Electronics & Power Supply	-25/50	10 ⁽²⁾		-10/40
Camera Head Electronics	-25/50	5 ⁽³⁾		-10/20
Diodes	-25/45	5		0/10
Optical Bench	-25/50	10 ⁽⁴⁾	< 3	0/10
Aperture Cover Motor	-45/65	10 ⁽⁴⁾		-35/55
Goniometer	-45/60	10 ⁽⁴⁾		-35/55
Calibration Plate Motor	-45/65	10	20	-35/55
Camera Lens (Barrel)	-25/50	2 ⁽⁵⁾	< 2	0/10
Glass Lens Elements	-25/50	5	< 0.4	0/10
Detectors (CCD)	-35/50			-5 ± 0.1K

- 10C max variation per orbit at electronics side of thermal interface.
- 10C max variation per orbit at electronics side of thermal interface. Additional 20C max variation within electronics assemblies per power on/off cycle in flight.
- 5C max variation per orbit at electronics side of thermal interface. Additional 10C max variation within electronics assemblies per orbit or total of 15C max at part solder joint.
- 10C max variation per orbit at thermal interface for mechanism electronics. Additional 20C max variation within electronics assemblies for each mechanism operation (electronics on/off cycle).
- As measured at optical mounting flange.

Table 4. Science mode instrument power profile

Component	Day Side (Watts)	Night Side (Watts)	Orbit Ave. (Watts)
TEC/CCD/FP heater (9 total)	6.2	6.2	6.2
Camera head electronics (9 total)	1.6	0	0.9
Camera support electronics (9 total)	49.1	0	26.5
Sys log, sys com & Computer	14.0	14.0	14.0
System power supplies	24.3	24.3	24.3
Electronics subtotals:	95.2	44.5	71.9
Optical Bench Operational Heaters	32.0	32.0	32.0
Totals:	127.2	76.5	103.9

THERMAL DESIGN

The instrument design incorporates both passive and active thermal control techniques to provide the temperature zones required by the instrument.

The overall instrument thermal design focuses on three thermal control zones; (1) focal plane temperature zone at -5°C for the CCD detectors, (2) optical bench zone at 5°C for the cameras including the camera head electronics and (3) room temperature zone near 20°C for the camera support electronics, power supply and system electronics. The -5°C zone within each camera head is provided by means of a TEC. A small silver flexible S-shape cold link is used to thermally couple the cooler cold junction to the focal plane. The CCD detector dissipation is 90 mW. The 5°C zone is provided by means of the TEC nadir radiator attached to the optical bench (see Figs. 21 and 22). The 20°C zone is achieved by means of separate nadir facing radiators.

The -5°C zones are contained within each of the nine camera heads. This temperature is control by means of a closed-loop control scheme with a small 100 mW heater and temperature sensor on the focal plane. The TEC is run at constant current providing nearly constant refrigeration capacity and the heater is used to control the setpoint temperature. The TEC power dissipation is approximately 0.5 W. All nine camera barrels attach to the optical bench, which is maintained at 5°C . The power dissipation in each camera assembly, which includes power from the TEC and camera head electronics, is dumped to the optical bench. The 5°C zone temperature is maintained by means of the TEC nadir radiator and a close-loop temperature control scheme with heater power control authority of 35 W. This provides greater than 15°C control range over the life of the instrument. It was designed such that at BOL, the heater controller would be operating at about 90% of maximum capacity and would gradually decrease as the instrument ages. During the cold condition under safe mode, the heater operates at full power (35 W) to maintain the optical bench within non-operating limits. The optical bench assembly has a large thermal time constant and for this reason it behaves much like a constant temperature heat sink. It is design with high longitudinal conductance resulting in only a $2\text{-}3^{\circ}\text{C}$ worse case spatial gradient. The optical bench configuration is similar to that of a "V8" automobile engine block and is machined from a single piece of 6061-T6 aluminum (Fig. 8).

The parasitic heat leak to the -5°C zone is minimized by means of three concentric tubes for thermal isolation and MLI blankets. One of the three tubes is made from fiberglass to minimize heat conduction (Fig. 23). The silver S-link and the TEC are covered with 5 layer MLI blankets. The estimated total heat load on the cooler cold junction is less than 75 mW at -5°C .

The optical bench assembly, including all nine cameras, are covered with a 15 layer MLI blanket. The optical bench is mounted to the base structure with five low conductance titanium struts. Fig. 8 illustrates the strut design. The optical bench nadir side, containing the camera apertures, has special thermal features to minimize the impact of orbital thermal environment variations. A single aluminum radiation shield is attached to the nadir surface of the optical bench. The optical bench and radiation shield surfaces with a view to each other are polished aluminum surfaces. The nadir side of the radiation shield is painted black to minimize stray light effects. This shield is thermally isolated from the optical bench.

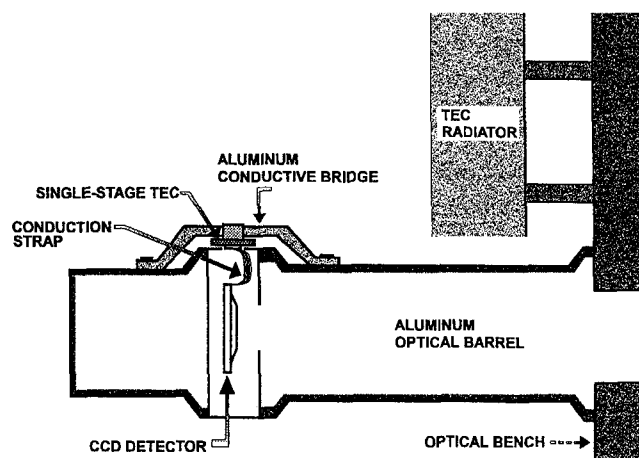


Figure 21. Conductive heat transfer path from TEC to radiator

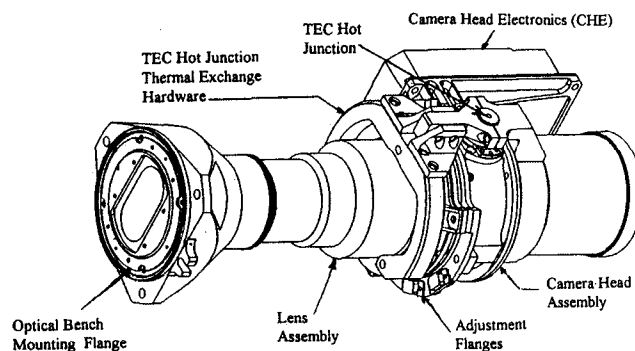


Figure 22. Typical camera barrel with camera head electronics

The electronics and TEC radiators make use of the spacecraft nadir side to maintain a stable thermal environment for the instrument. The electronics and TEC radiator surface areas are 0.475 and 0.238 m^2 , respectively. The electronics radiator consists of two surfaces designated as $-X$ and $+X$ electronics radiators while the TEC radiator consists of three separate

surfaces designated as -X, +X and +Y TEC radiators. The radiators are fabricated from 5005-T6 aluminum and are painted with HINCOM white paint to minimize solar heating. The radiators were optimized for high efficiency with an acceptable mass by profiling the thickness. The radiators vary from 40 to 200 mils thick. The +Y and -X glint baffles are painted white outboard and black inboard. The -X glint baffle, of Kapton sheet construction, is painted black on both sides. The inboard black paint surface minimizes stray light effects.

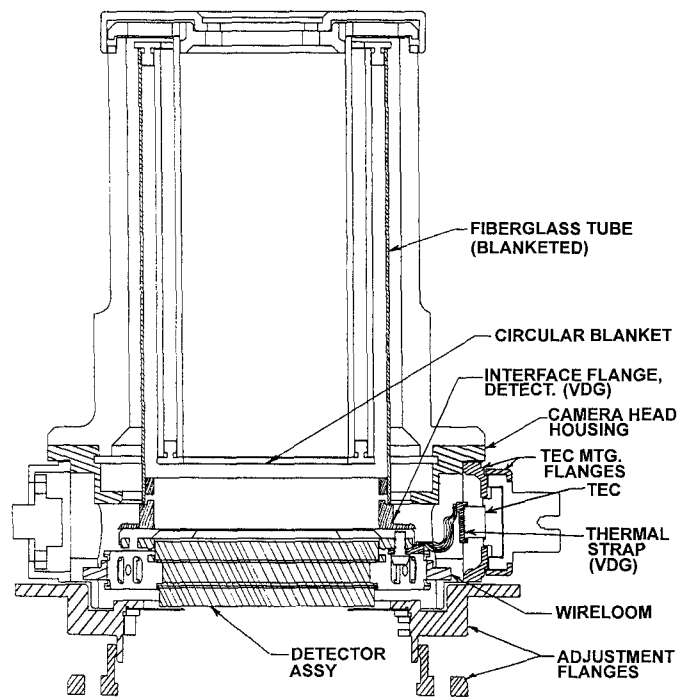


Figure 23. Fiberglass tube focal plane thermal isolation scheme

The waste heat from all the components is conducted to the heat rejecting nadir radiator surfaces. While in survival mode, the instrument is not operating and the survival heaters maintain equipment temperatures within the allowable non-operating limits. In safe mode, the spacecraft attitude is such that the effective sink temperature for the radiator panels drops from -25°C to -96°C. To maintain equipment temperatures within non-operating cold limits, the system electronics remains powered, replacement heaters are used for the remaining electronics and the optical bench heater remains powered.

The deployable aperture cover when stowed serves two functions on-orbit. First, it protects the camera apertures from contamination and other potentially damaging space environments such as meteorites and atomic oxygen. Secondly, it provides additional thermal isolation from cold space equivalent to about 15 W when pointing to cold space.

In science mode, the camera support electronics are powered off during the night side of each orbit. This was required to reduce the orbit average operating power to stay within the allocated budget and to keep within the data rate limits. The on-off power cycling increases the electronic component orbital peak-to-peak temperature variation. Due to the higher than expected available spacecraft power in orbit, in the next several weeks, MISR will be commanded to keep the cameras powered throughout the orbit. The orbital peak-to-peak temperature variation will be significantly reduced, and therefore, the life expectancy of the electronics will increase.

MISR is instrumented with 132 thermistors read by the onboard computer and 7 thermistors, referred to as passive analog, read by the spacecraft for health monitoring when the instrument is off. Temperature telemetry from the passive analog sensors is available continuously.

Table 5. Instrument surface coatings

Item		Surface Type	Surface Properties	
			BOL (α / ϵ)	EOL (α / ϵ)
Electronics radiator		White paint (HINCOM)	0.15/0.90	0.25/0.90
TEC radiator				
Optical bench cover		Bare aluminum	0.15/0.05	0.15/0.05
Optical bench thermal shield		Black paint (Z306)	0.95/0.87	0.97/0.85
Optical bench cover motor housing		15 layer-Mylar 1 mil carbon filled Kapton outer layer	0.92/0.88	0.92/0.88
-X and +Y Glint baffles	Inboard	White paint (HINCOM)	0.15/0.90	0.25/0.90
	Outboard	Black paint (Z306)	0.95/0.87	0.97/0.85
-X Glint baffle		Black paint (Z306)	0.95/0.87	0.97/0.85
MLI optical bench		15 layer-Mylar 1 mil carbon filled Kapton outer layer	0.92/0.88	0.92/0.88
MLI instrument		3 mil aluminized Kapton	0.38/0.65	0.42/0.63
MLI instrument* (external MLI)		15 layer-Mylar	0.025	0.035
MLI optical bench* (interior MLI)		15 layer-Mylar	0.020	0.035

* Values denote MLI effective emissivity

THERMAL ANALYSIS

Instrument thermal analysis was performed using a reduced geometric math model (RGMM) developed with the Thermal Radiation Analyzer System (TRASYS) software package and reduced thermal math model (RTMM) developed in SINDA85 format. The RGMM consist of 169 surfaces and the RTMM contains 165 thermal nodes. Isometric views of the RGMM are shown

in Figs. 24 and 25 and a top view is shown in Fig. 26. The TEC radiator is modeled with surface nodes 42014, 42016 and 42020 while the electronics radiator is modeled with nodes 42012 and 42021.

The RGMM and RTMM were delivered to the spacecraft integrator for inclusion in the overall spacecraft thermal analysis. From the spacecraft-level thermal analysis, environmental heat fluxes and infrared backloads were generated for inclusion in the stand-alone instrument models.

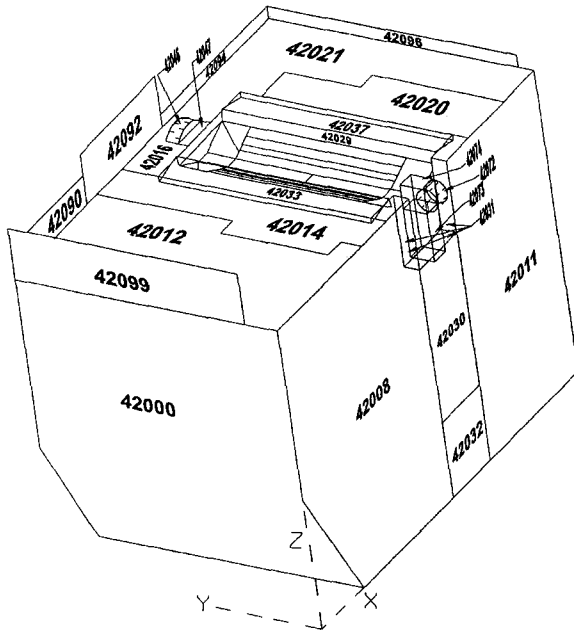


Figure 24. Instrument RGMM: aperture cover deployed configuration

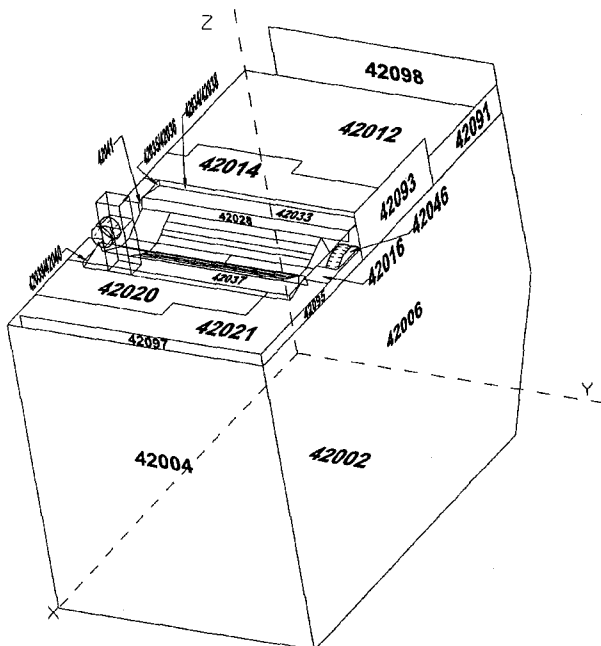


Figure 25. Instrument RGMM: +X, +Y isometric

Early in the design process, very detailed unit level thermal models were developed to be able to carry out trade studies and identify the sensitivity of various parameters including geometry. These included models for the optical bench including its cover, camera barrel assemblies and CCD focal plane assemblies, TEC and electronics radiators.

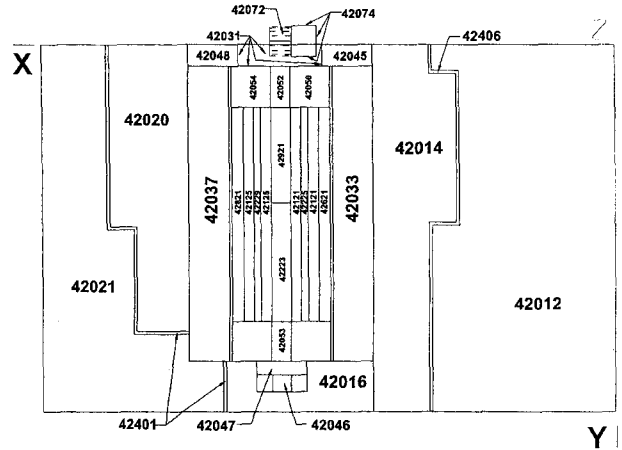


Figure 26. Instrument RGMM: top view (+Z side)

The reduced and detailed models were run for the cold, hot, safe and survival cases. The models include logic to simulate heater circuits with thermostatic control. Orbital transient as well as orbit average steady state simulations were run.

ANALYSIS RESULTS

The analysis results show that the thermal control system meets all the specified temperature control requirements. In general, the results from both the reduced and the unit level models agree quite well.

Table 6. Radiator orbit average absorbed heat flux

Radiator	Abs. Flux (W/m ²)	Case			
		Science Min-Cold	Science Max-Hot	Survival	Safe
+X Electronics	Solar	20.7	36.2	20.7	2.3
	IR	153.3	171.4	163.5	44.5
	Total	174.0	207.6	184.2	46.8
-X Electronics	Solar	18.8	33.5	18.8	2.6
	IR	153.3	160.7	153.3	38.4
	Total	172.1	194.2	172.1	41.0
+X TEC	Solar	22.6	39.6	22.6	2.8
	IR	170.2	178.2	170.2	47.9
	Total	192.8	217.8	192.8	50.7
-X TEC	Solar	21.9	38.6	22.0	2.6
	IR	164.2	172.1	164.3	43.5
	Total	186.1	210.7	186.3	46.1
+Y TEC	Solar	18.7	32.8	18.8	1.9
	IR	130.2	136.6	130.3	32.0
	Total	148.9	164.4	149.1	33.9

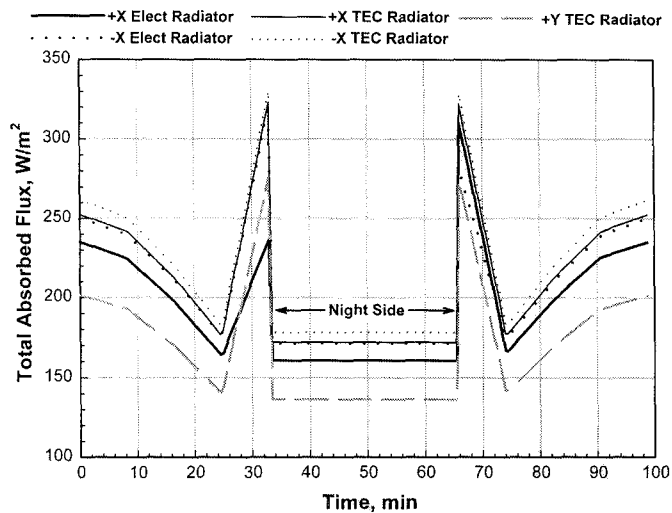


Figure 27. Nadir radiator absorbed heat flux: **hot case**

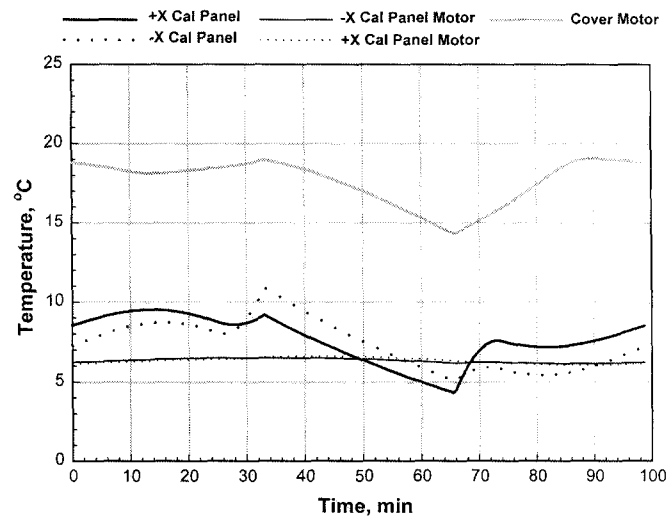


Figure 30. Predicted transient temperatures: calibration panels and cover motor - **hot case**

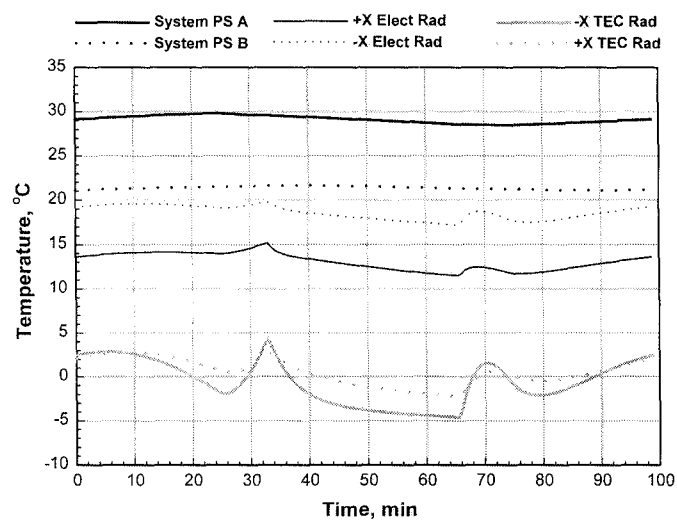


Figure 28. Predicted transient temperatures: electronics and radiators - **hot case**

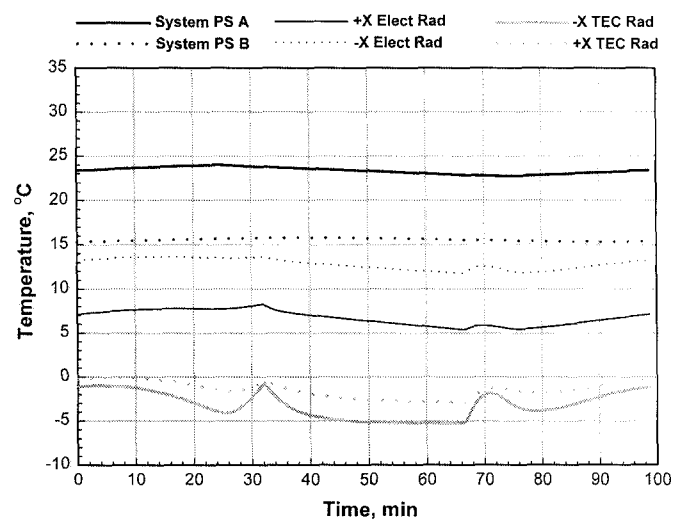


Figure 31. Predicted transient temperatures: electronics and radiators - **cold case**

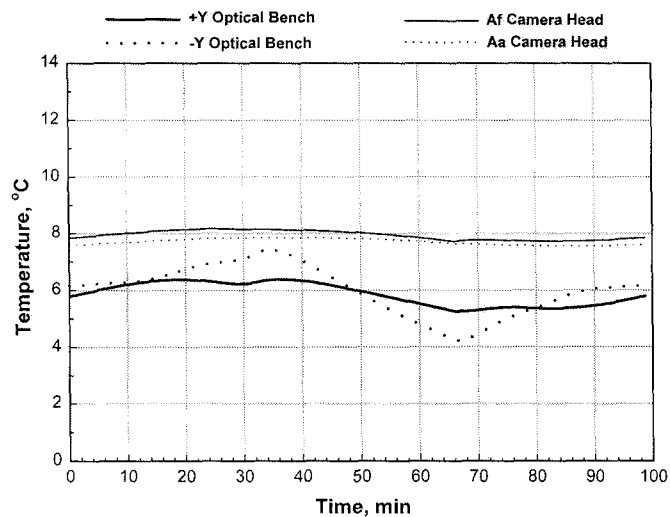


Figure 29. Predicted transient temperatures: optical bench and camera head electronics - **hot case**

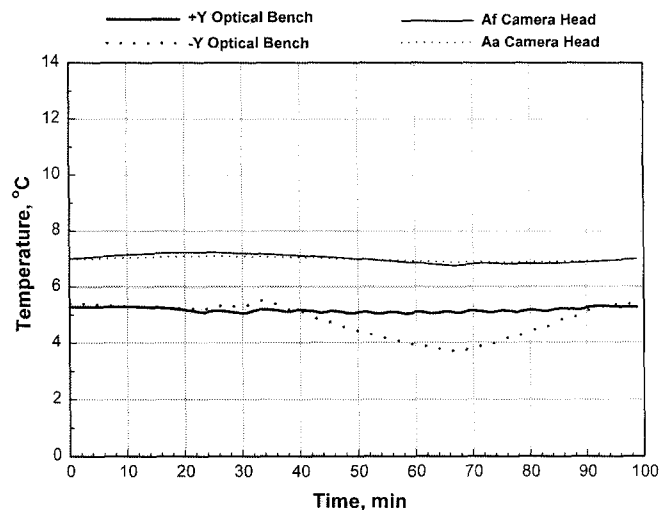


Figure 32. Predicted transient temperatures: optical bench and camera head electronics - **cold case**

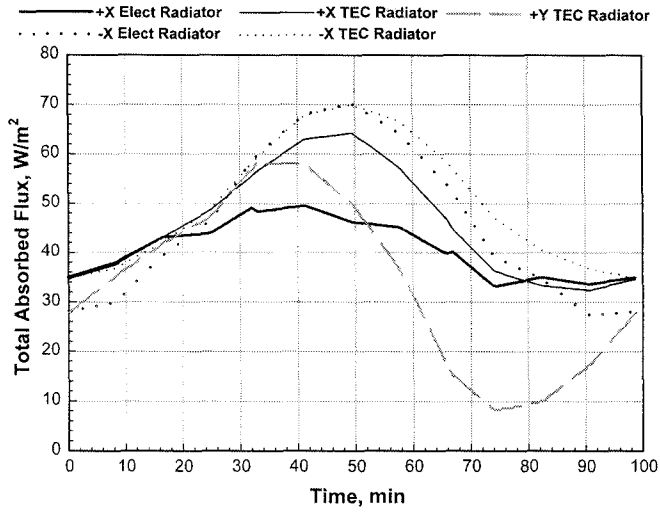


Figure 33. Nadir radiator absorbed heat flux: **safe case**

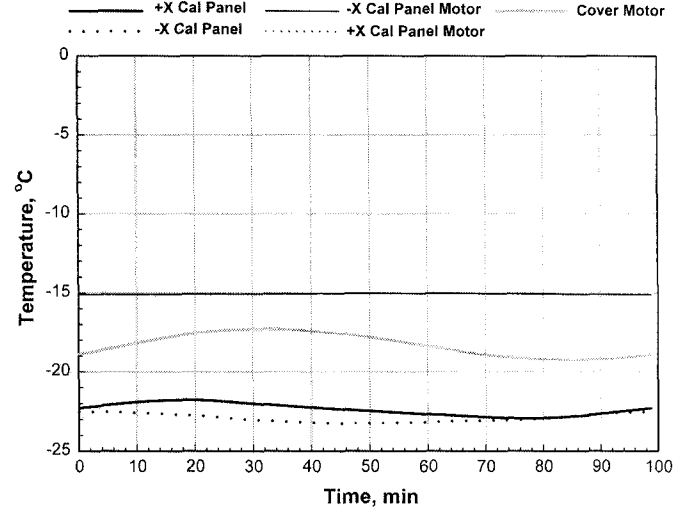


Figure 36. Predicted transient temperatures: calibration panels and cover motor - **safe case**

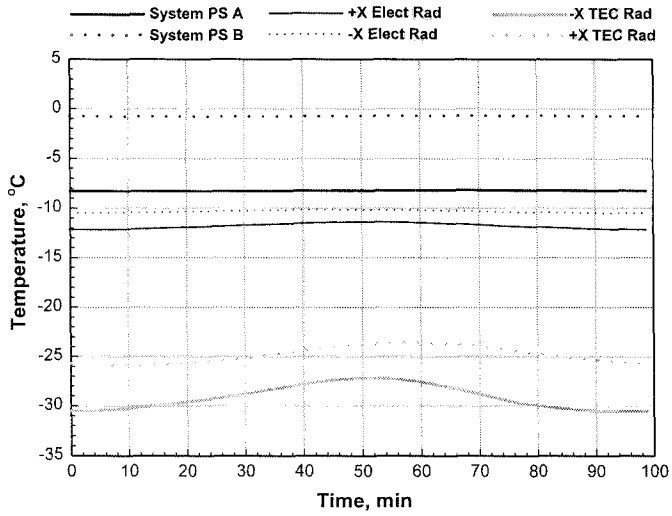


Figure 34. Predicted transient temperatures: electronics and radiators - **safe case**

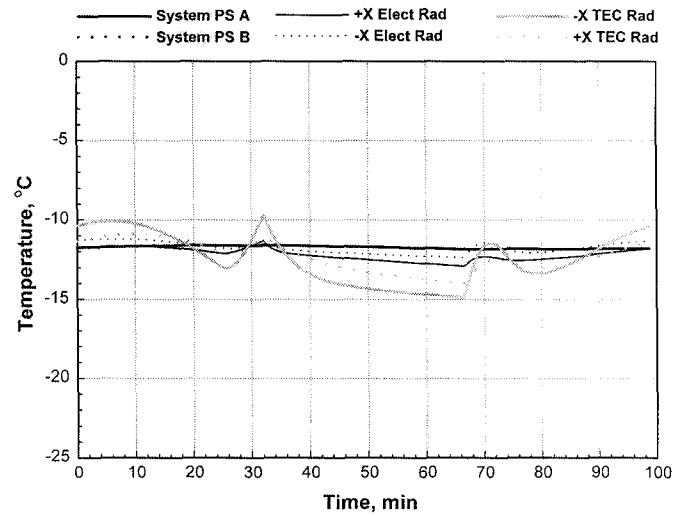


Figure 37. Predicted transient temperatures: electronics and radiators - **survival case**

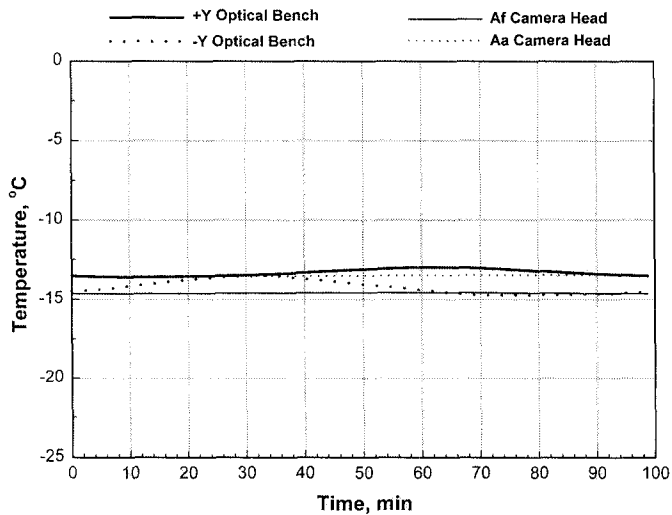


Figure 35. Predicted transient temperatures: optical bench and camera head electronics - **safe case**

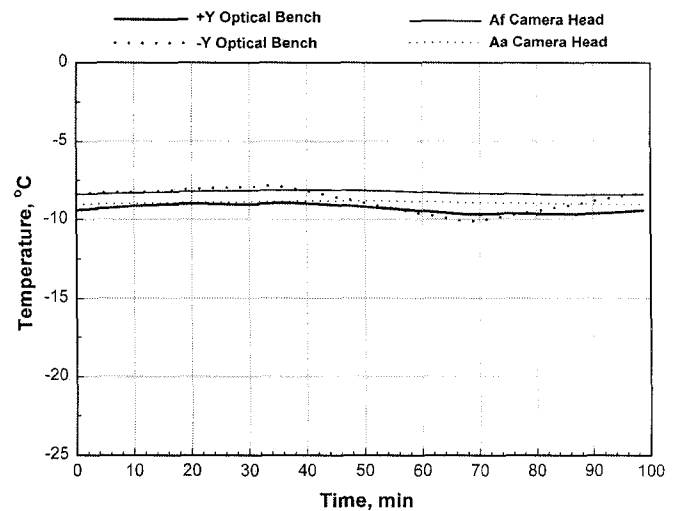


Figure 38. Predicted transient temperatures: optical bench and camera head electronics - **survival case**

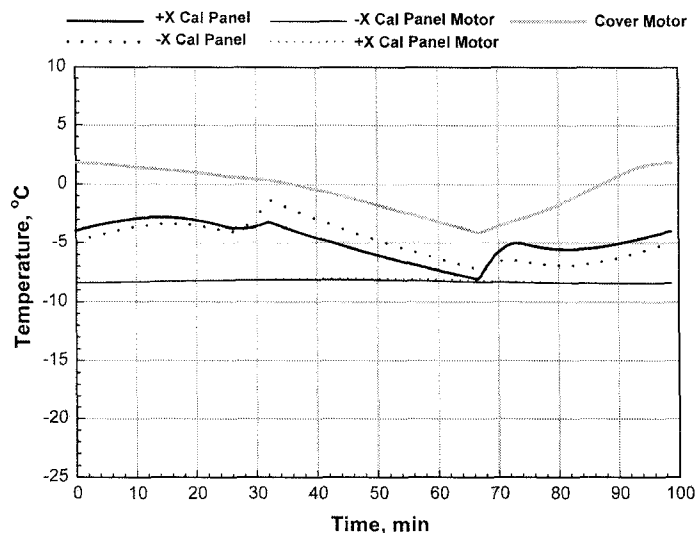


Figure 39. Predicted transient temperatures: calibration panels and cover motor - **survival case**

Table 7. Flight temperature prediction summary

	Flight Temperature Predictions (°C)					
	Operating				Non-operating ⁽¹⁾	
	Cold Case		Hot Case		Surv	Safe ⁽⁴⁾
	Orbit var. ⁽²⁾	Orbit ave. ⁽³⁾	Orbit var. ⁽²⁾	Orbit ave. ⁽³⁾		
Camera Support Electronics	3	6/16	3	13/22	-12	-10
System Electronics & Power Supply	1	15/24	1	21/30	-12	-8
Camera Head Electronics	0.5	6/7	0.5	7/8	-9	-15
Diodes	3.9	3/8	4.4	4/9	-10	-15
Optical Bench	3.9	3/8	4.4	4/9	-10	-15
Aperture Cover Motor	6	5/11	5	14/19	-4	-19
Goniometer	2	5/7	1	9/10	-8	-19
Calibration Plate Motor	0.4	5/6	1	6/7	-8	-15
Camera Lens (Barrel)	3.9	3/8	4.4	4/9	-10	-15
Glass Lens Elements	3.9	3/8	4.4	4/9	-10	-15
Detectors (CCD)	n/a	-5	n/a	-5	-10	-15

1. Non-operating temperatures are minimum values.

2. Worst case variation for a single node.

3. Includes range for all nodes.

4. Replacement and optical bench heaters powered on.

The absorbed orbit average fluxes for the radiators are shown in Table 6. Results from the orbital transient simulations with the reduced models for science, safe and survival modes are shown in Figs. 27-39. A summary of the temperature predictions is shown in Table 7. Results show a comfortable temperature margin for all scenarios.

INSTRUMENT LEVEL THERMAL BALANCE TEST

ENGINEERING MODEL

The MISR engineering model (EM) instrument thermal balance test which included bakeout and decontamination phases was conducted June 3-16, 1995 in JPL's vertical 10 foot space simulator chamber. The thermal balance test primary objectives were to validate the thermal control system and to expose the instrument to a wide range of thermal vacuum environments in order to verify and validate the thermal models. During the thermal balance test, known thermal environmental conditions were established and the instrument response was measured when it was in thermal balance with those conditions.

To maintain a high level of confidence on the flight correlated model, both the test fixture and the thermal stimuli were designed to produce flight-like thermal boundary conditions. Every effort was made to simulate, as close as possible, the predicted environmental flight conditions. To simulate flight conditions, MISR was configured with flight-like mechanical, electrical and thermal interfaces. Cameras assemblies Anadir and Daft and their associated camera head electronics and camera support electronics were flight-like, the remaining seven cameras and associated electronics were dummy thermal simulators with heaters. Only string A of the system electronics consisting of syscom, computer A, syslog A and syspwr A was operational. The dummy camera assemblies were thermally representative of the protoflight units with the appropriate thermal masses, heater power dissipation and mounting interfaces. The aperture cover was the only operational mechanism. The spacecraft was simulated with a temperature controlled mounting plate and the thermal radiation boundaries were simulated with a combination of liquid nitrogen shrouds, infrared heat lamps and test heaters. Figs. 40 and 41 show the test configuration.

The instrument thermal model was modified to generate a test model representing the test configuration with test fixture and thermal stimuli. The test model was then used in the correlation process and was considered verified when the difference between the test model predictions and the test data was acceptable. A correlated model was then extracted from the verified test model to demonstrate the validity of the thermal control system and make flight predictions. Flight predictions using this correlated model established the ability of the thermal control system to maintain all equipment within specified temperature limits for all mission phases. An additional test objective was to gain confidence in the overall test approach, required procedures, and hardware performance to use for the protoflight model thermal vacuum test. All the outlined

objectives were met successfully. During the test a number of minor problems surfaced which were solved fairly quickly without impacting the test objectives. The difficulties encountered were related to support test hardware and software. A comprehensive thermal test report was written to document the approach and test results (Ref. 5).

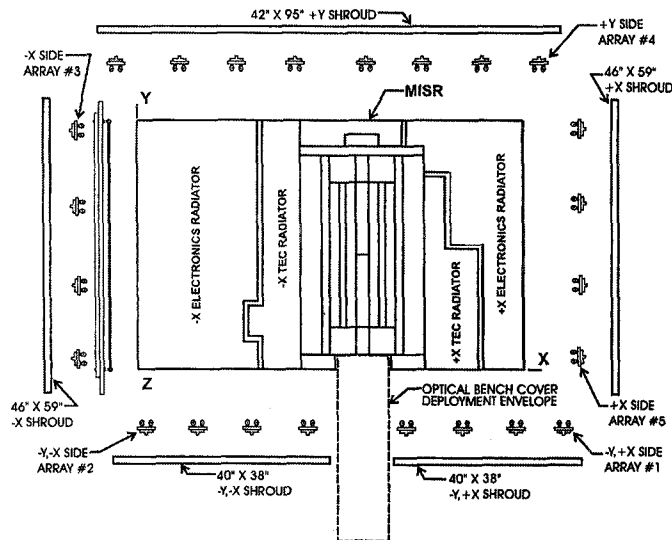


Figure 41. Instrument level thermal vacuum test fixture: top view

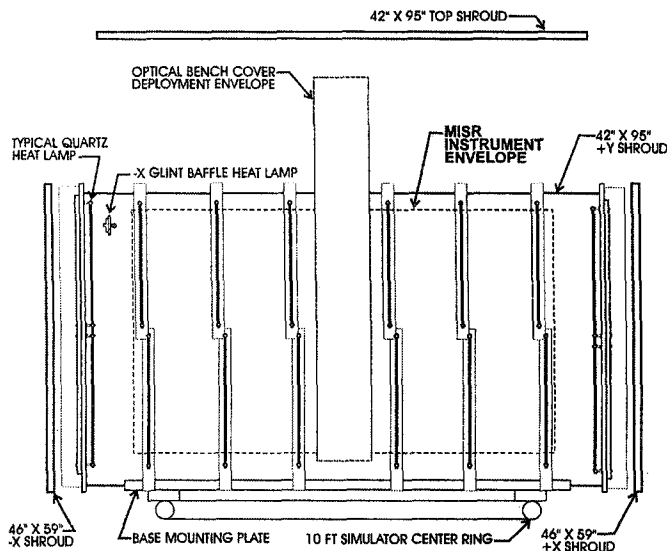


Figure 40. Instrument level thermal vacuum test fixture: side view

PROTOFLIGHT MODEL

The MISR protoflight model (PFM) was subjected to the expected space vacuum thermal environments during a 13 day period from December 9 to December 21, 1996. The same test approach, test hardware and procedures from the MISR EM thermal balance test were used to

carry out this test. The purpose was to verify the thermal control system and to correlate/ validate the thermal models with the flight instrument. Fig. 42 shows MISR in the vertical 10 foot space simulator chamber. During this test, a number of thermal problems with the ground support equipment were encountered, but were solved quickly without significant impact to the test objectives or schedule. After completion of the test, it was determined that the thermal balance test was successful. However, major system-level problems surfaced which precluded the successful demonstration of end-to-end system-level operation and robustness over temperature and voltage. Upon completion of the test, flight software and hardware modifications were implemented to fix the system-level problems encountered and a second system-level thermal vacuum test was carried out May 6-13, 1997. The second PFM thermal vacuum test did not include a thermal balance test. The primary objective of this second test was to demonstrate successful end-to-end system-level operation and robustness over temperature and voltage. Overall the instrument performed well and showed that the PFM was capable of successful operation from an engineering perspective, which includes functionality of mechanisms, command responses, telemetry and science data output under various operating modes and simulated orbital conditions. There were no thermal control system issues during this test. A thermal test report was written and is found in Ref. 6.

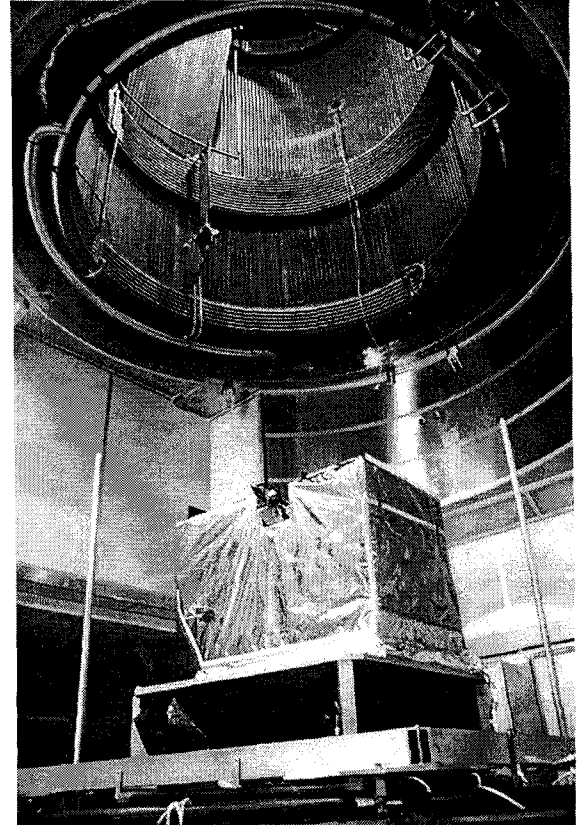


Figure 42. MISR protoflight model in JPL's vertical 10 foot vacuum chamber

The instrument was delivered to Lockheed Martin for integration on the Terra spacecraft. After integration, MISR once again went through thermal vacuum/ balance test at spacecraft-level. During this test, there were no thermal issues with MISR. Fig. 43 shows MISR on the Terra spacecraft.

FLIGHT THERMAL PERFORMANCE

To date, the on-orbit temperature telemetry data shows the thermal control subsystem operating as expected. All temperatures are well within the AFTs. On-orbit temperature data for science mode is plotted in Figs. 44-50. All the equipment temperatures are near the nominal temperatures predicted. The cameras and associated electronics are turned off on the night side of the orbit, and therefore, there is no telemetry available from the cameras during this period. This is shown in Figs. 48 and 49. The focal plane temperatures are controlled to within ± 60 mK as shown in Fig. 50 for camera Bf. Data from Fig. 50 shows that there is considerable noise pickup in the focal plane temperature measurement for almost 2 minutes every 10 minute cycles. It is believed that this is due to the focal plane heater operation. The CCD temperatures are within the AFT limits.

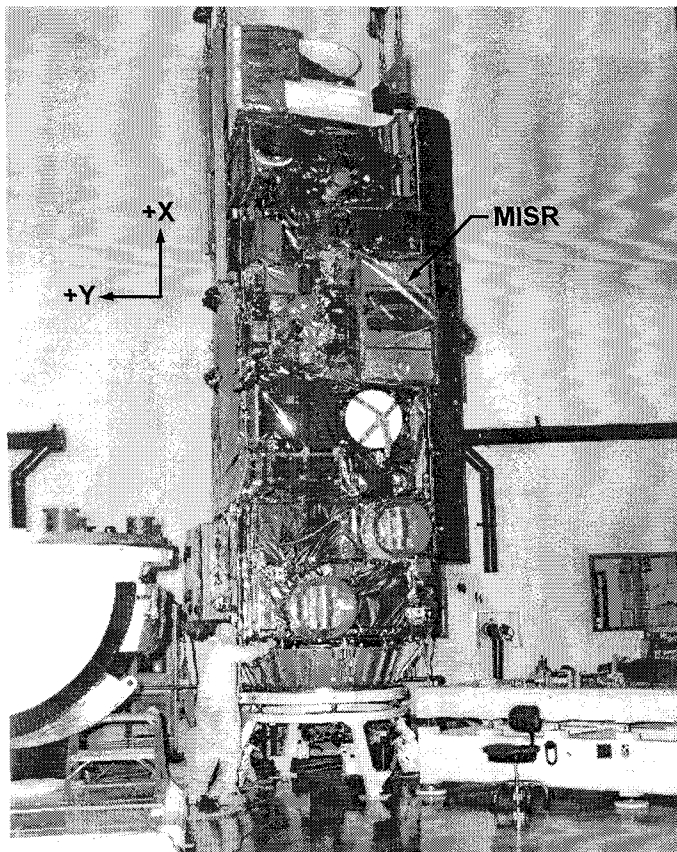


Figure 43. Terra spacecraft at Lockheed Martin, Valley Forge, Pennsylvania, prior to spacecraft-level thermal vacuum/ balance test

At the time of this writing, the spacecraft has been in orbit for fifteen months operating successfully primarily in science mode. The spacecraft has been commanded to safe and survival modes for short periods of time. While in safe and survival mode, the thermal control subsystem has operated nominally. The on-orbit thermal model predictions have compared favorably with the flight temperature data.

CONCLUSIONS

Instrument and unit level thermal models were developed for MISR. These models demonstrated that an acceptable thermal performance for MISR was to be expected on-orbit for all phases of the Terra mission. The results presented show a robust thermal control design. Adequate temperature margins for all environmental conditions and instrument modes were demonstrated.

The instrument thermal design, as illustrated from on-orbit temperature telemetry data, shows that an acceptable thermal performance can be expected for the remaining of the six-year Terra mission. The thermal design, which includes passive and active thermal control hardware, maintains all the equipment within the AFTs with margin.

The science data obtained to date has resulted in remarkable images of Earth. The science team has just recently completed the development of the necessary tools to extract scientific data from the wealth of information being acquired by MISR.

ACKNOWLEDGMENTS

We would like to thank the JPL MISR team as well as all the subcontractors that contributed to the development of the MISR instrument. We would like to recognize the support of the MISR flight operations team.

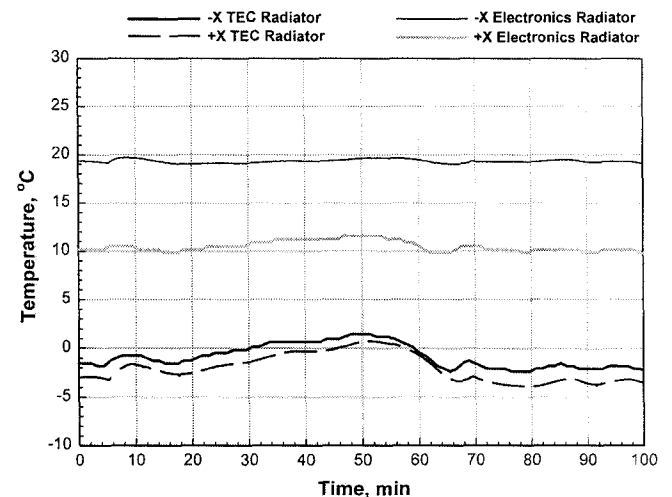


Figure 44. On-orbit radiator temperatures

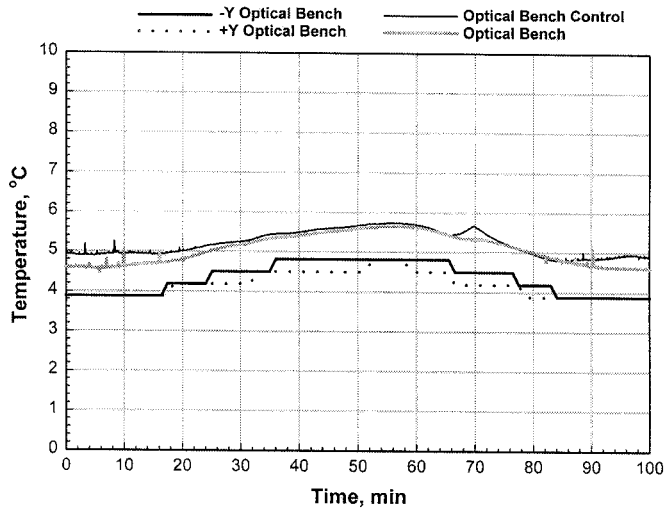


Figure 45. On-orbit optical bench temperatures

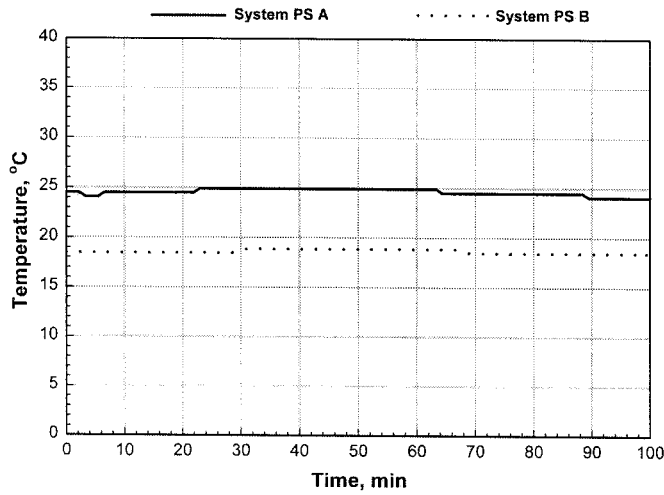


Figure 46. On-orbit system power supply temperatures

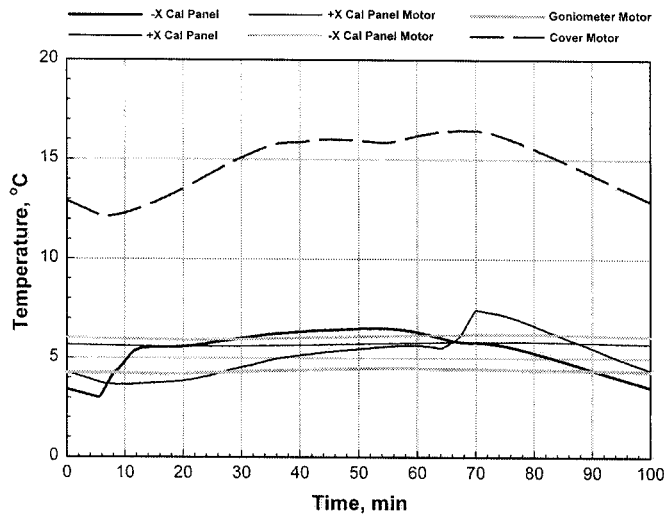


Figure 47. On-orbit calibration panel, cover and goniometer motor temperatures

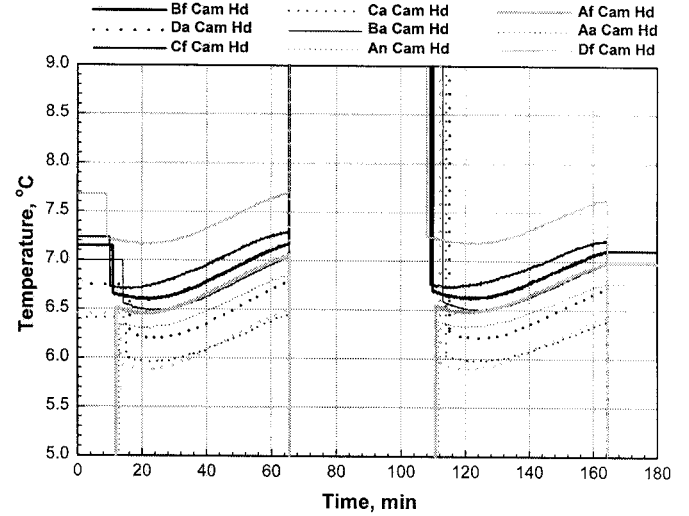


Figure 48. On-orbit camera head electronic temperatures

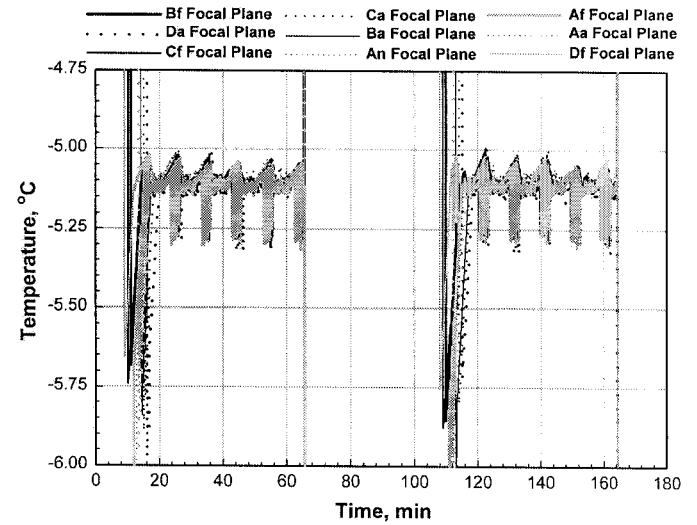


Figure 49. On-orbit focal plane temperatures

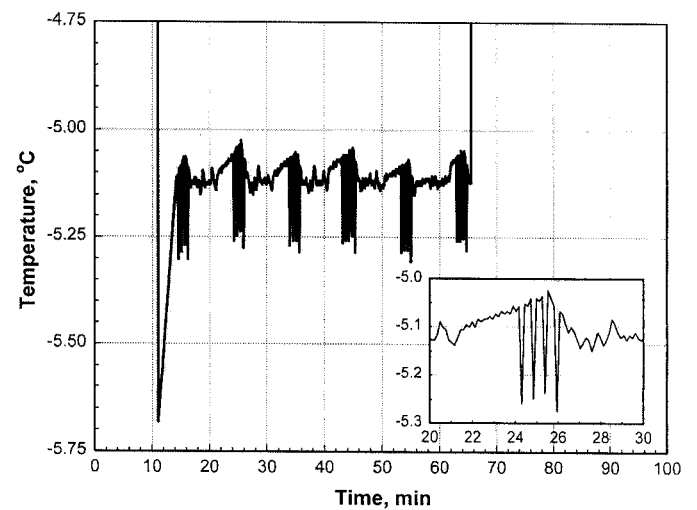


Figure 50. On-orbit Bf camera focal plane temperature

The research described in this paper was partially carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. Diner, D., Beckert, J., Reilly, T., Bruegge, C., Conel, J., Kahn, R., Martonchik, J., Ackerman, T., Davies, R., Gerstl, S., Gordon, H., Muller, J-P., Myneni, R., Sellers, P., Pinty, B. and Verstraete, M., "Multi-angle Imaging SpectroRadiometer (MISR) Instrument Description and Experiment Overview," IEEE Trans. Geosci. Rem. Sens. 36, p. 1072-1087, 1998.
2. Diner, D.J., et. al., "A Multi-angle Imaging SpectroRadiometer for Terrestrial Remote Sensing from the Earth Observing System," International J. Imaging Systems and Technology, Vol. 3, p. 92-107, 1991.
3. Diner, D.J., "EOS Multi-angle Imaging Spectro-Radiometer," Remote Sensing of the Biosphere, Proc. SPIE 1300, p. 163-177, April 1990.
4. Diner, D.J., et. al., "MISR: A Multi-angle Imaging SpectroRadiometer for Geophysical and Climatological Research from EOS," IEEE Trans., Geoscience and Remote Sens., Vol. 27, No. 2, p. 200-214, March 1989.
5. Holbeck H., et. al., "Composite Primary Support Structure for the Multi-Angle Imaging Spectro-Radiometer (MISR)," AIAA Paper No. 981587, July 1996.
6. Rodriguez, J.I., "MISR Engineering Model Thermal Balance Test Report," JPL Internal Document, D-13039, November 1995.
7. Rodriguez, J.I., "MISR Protoflight Model Thermal Balance Test Report," JPL Internal Document, D-14719, August 1997.

CONTACT

For additional information contact: Dr. Jose I. Rodriguez at the Jet Propulsion Laboratory. Phone:(818)354-0799. Email: Jose.I.Rodriguez@jpl.nasa.gov